WAVE CUT TESTS TO OPTIMIZE HULL FORM CHANGES

By:

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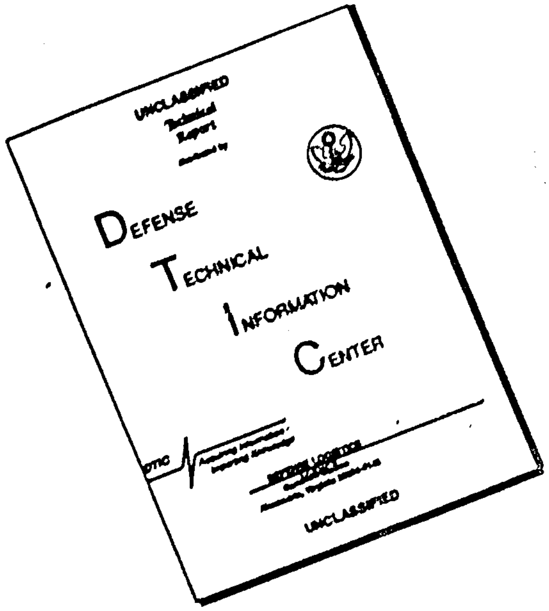

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NOMENCLATURE

A	Centerline Wave Amplitude, Ft.
A_1, A_2	Wave Optimization Factors
$\overline{AB}$	Distance Between Point A and B, Ft.
A,B,C,D	Points, See Figure 1
b	Model Tank Width, Ft.
B	Model Beam, Ft. or Bulb Size Designation
B_1, B_2	Wave Optimization Factors
C	Wave Optimization Factor
C_w	Wave Resistance Coefficient = $R_w/\rho/2SV^2$
D	Wave Optimization Factor
Δ	Model Displacement, Lb.
F_r	Froude Number = $V/\sqrt{gL}$, Non-Dimensional
g	Gravitational Constant, Ft/Sec^2
H	Model Draft, Ft. or Bulb Depth Position (See Figure 2)
I	XY Integral, Ft.
k	Ratio of linear dimension of a hull form variation considered, i.e. a bulb or protuberance, to that used in the model test. Also used as a subscript, thus, 0 would refer to the bare hull test and 1 to the bulb test, and 2 to the protuberance test.
opt	Subscript denoting optimum (best) value of a parameter for a particular bulb or protuberance shape and location.
λ	Scale Ratio
L	Length of Model, Ft.
m	Percentage saving of bare hull wave resistance by use of a bulb or protuberance at some location.
n	Exponent of the bulb or protuberance dimension k to which the wave height is proportional, i.e. n = 2 would assume the wave height to vary with bulb area.
N	Run Number

NOMENCLATURE CONTINUED

P	Protuberance Designation
ρ	Density of Fluid, Slugs/Ft^3
R_w	Wave Resistance, Lbs.
S	Model Wetted Surface, Ft^2
T	Superscript Denoting the Result Includes the Truncation Correction
V	Speed
V_m	Speed of Model, Ft/Sec
x	Coordinate in Direction of Model Travel (See Figure 1)
X	Force on cylinder in x-direction, reduced by calibration to ft. of wave elevation, or bulb station designation.
y	Coordinate perpendicular to direction of model travel (See Figure 1) perpendicular to x.
Y	Force on cylinder in y-direction, reduced by calibration to ft. of wave elevation.
Z	Wave Elevation at Measuring Station, Ft.

SUMMARY

Research was continued in the towing tank at Webb Institute using the established XY wave survey method for determining ship model wave resistance from measurements of the force exerted on a stationary vertical cylinder by the waves produced by the model. As before, the hull form used was the Maritime Administration "Security Class" Multi-Purpose Mobilization Ship (MMS).

New results using this technique showed (a) that a Kawasaki-type stern bulb caused a small saving (7 percent) of wave energy; (b) ~~that~~ a suggested vertically distributed bow bulb area was not better than the originally designed elliptical distribution; and (c) ~~that~~ a newly developed two-change optimization theory (included in the text) was valid and that the predicted bow bulb-Station 4 protuberance combination was in fact beneficial. The large percentage (about 67 percent) saving in wave resistance caused by these additions does not seem to be identifiable by simply comparing the wave signals by eye.

Tests to assess the possible adjustment of the above wave resistance savings to those of wave power by including the effect of average wake values in the propeller disc were made, and it is concluded that such changes were not significant for the present model and bulbs.

INTRODUCTION

The following is a summary of results under the projects (1), (2), (3) and (4)* carried out under the Maritime Administration's University Research Program utilizing a method for assessing ship hull forms from a resistance point of view by an experimental technique of measuring wave resistance in the model tank called the XY Method of Wave Survey. Table 1 shows a summary of this effort. The ultimate objective of these studies is the determination of improved hull forms requiring less power, a question of increasing importance because of continuing high fuel prices. Reports (2), (3) and (4) on the previous studies have been issued and include a discussion of the background of ship wave theory in general and of the XY wave survey method in particular as well as the optimization technique used in analyzing the experiments to deduce the best possible sizes of tested hull form variations from a wave power loss point of view. The XY method is discussed in more detail in References (5) and (6). Only a brief summary of the approach will be included here.

The present study continues the previous investigations of wave-producing qualities of a particular hull, the Mar Ad Multi-Purpose Mobilization Ship, but as redesigned (7), with and without bulbs or other protuberances with the goal of using such assessments in an efficient way to determine optimum size and shape of such hull form changes for a particular Froude number F_r** and loading condition.

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* Numbers in parentheses denote references listed on Page 78.

** $F_r = V/\sqrt{gL}$ where V = speed of hull, L = length of hull, g = gravitational constant.

TABLE 1

SUMMARY OF WAVE SURVEY RESEARCH AT WEBB INSTITUTE UNDER THE MARITIME ADMINISTRATION UNIVERSITY RESEARCH PROGRAM

DATES FUNDING (1)	MINA NO. CONTRACT NO.	TITLE	MODEL(S)	BULB(S) & LOCATION(S)	F_R'S	LOADS	WAKE?	REPORT AUTHORS	WAVE ANALYSIS ETC.
5/30/78-12/01/79 $52,960	G-111 DO-A01-78-00-3125	"INITIAL PROGRESS IN DEVELOPMENT OF ... (2)"	(A) SERIES 60/.60 C_B (B) MPS-SHORT & LONG HULLS (3)	(A) CIRCULAR (B) ELLIPTICAL AT STATION 0.3	5 DESIGN &	FULL LOAD	—	MARCH 1980 TAM & RDS REFERENCE (9)	P.D.P. TAPE USED TO TIME SHARING
(1) 5/29/79-10/31/80 $53,275	G-136 MA-79-SAC-A0106	"UTILIZATION AND IMPROVEMENT OF ... (2)"	MPS-SHORT HULL (3)	ELLIPTICAL FULL AND HALF-SIZE AT STATION 0.1296 & 2 DRAFTS	3 & 2	FULL LOAD	RUN, NOT ANALYZED	MARCH 1981 TAM & PJM REFERENCE (3)	P.D.P. DISC STORAGE & ANALYSIS, CALIB. AUTOMATED
(1) 9/29/80-01 $30,979	G-143 MA-80-SAC-01079	"APPLICATION OF ... (2)"	MPS-RE DESIGNED "SECURITY" CLASS (3)	ELLIPTICAL, CIRCULAR & OTHER STATION 0 (& 4)	1 (DESIGN)	FULL LOAD MEDIUM BALLAST LIGHT BALLAST	RUN & ANALYZED AND COMPARED	FEBRUARY 1982 TAM, PJM, & ER REFERENCE (2)	FURTHER AUTO OF CALIB. & SPEED MEASUREMENTS
(1) 9/01/81-12/01/82 $18,746	G-166 MA-81-SAC-10066	"FURTHER DEVELOPMENT AND APPLICATION OF ... (2)"	AS ABOVE	VARIOUS STATION 0 & STERN BULB & TWO CHANGES	5 DESIGN &	F, M, L AS ABOVE & FULL LOAD	—	JANUARY 1983 TAM, PJM, & ER	CALC. FOR TWO CHANGES IMPROVED CALIBRATION TECHNIQUES

(1) EXTENDED

(2) "AN EXPERIMENTAL METHOD TO OPTIMIZE THE WAVE POWER OF SHIPS"

(3) MULTI-PURPOSE MOBILIZATION SHIP

The latter variation and especially the question of behavior of the bulbs in light ballast condition was emphasized in the most recent (2) study. The latter will be continued in the present study. Also, investigation of possible wave resistance reduction benefits of a type of stern end bulb as has been proposed by Kawasaki (8) will be examined using the same ("one change") method developed for bow bulbs or protuberances. Finally, a "two-change" theory will be derived and applied to the same hull form, with a bow bulb and forebody protuberance as the two changes, and the optimum combination thus predicted also fitted on the model and a check test run. As before, the goal of the research is the continued improvement of the instrumentation and method of analysis and to demonstrate its potential use in improving the design of ship hull forms and appendages.

The Webb Model Tank, a 93 foot by 10' x 5' rectangular channel, and associated PDP 11 computer data acquisition and Minneapolis Honeywell Visicorder signal conditioning recording system, was used for the present study.

SUMMARY OF THE METHOD AND EXPERIMENTAL APPROACH

The theory and background of the XY wave survey method for obtaining an estimate of the wave making resistance, R_w, of a ship model from the waves produced during a run in a towing tank was originally proposed in Reference (5). This is brought up to date and the currently employed experimental techniques are outlined in detail in References (3) and (4). Only a brief outline will be included here. The analysis involves measuring the energy flux out of control volume ABCD shown in Figure 1. The key result (Equation 18 of Reference (5)) gives the wave resistance R_w as:

$$R_w = \rho g(I + 1/2\, \overline{AB}\, A^2)$$

Where: $$I = \int_{x_B}^{\infty} XY\, dx$$

and X, Y are the x, y components of the force exerted by the model wave system on a long thin vertically-oriented circular cylinder at a distance $y = \overline{AB}$ away from the model centerline converted, by means of calibration, to wave amplitude. The term $\rho g I$ measures the energy flux out of the line BC. That across CD is assumed to be zero. A is the amplitude of the following waves at $x = x_B$ at the point of truncation of the wave signals. The density and gravitation constants are ρ and g, respectively. Any consistent system of units can be used. In the present analysis, the "English" system will be employed, i.e. pounds, feet and seconds, or non-dimensional results will be reported. For the latter purpose, we will use a non-dimensional resistance coefficient C_w:

$$C_w = R_w/(\rho/2)SV_m^2$$

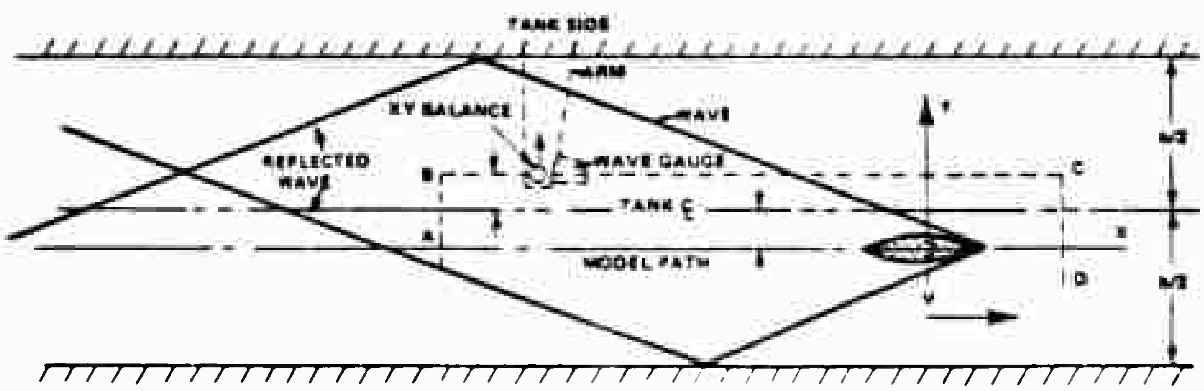


FIGURE 1: XY METHOD GEOMETRY

The term $1/2\ \overline{AB}\ A^2$ measures the energy flux through AB and is a "truncation" addition to the basic XY integration, I, due to the finite length of the record necessitated by avoiding any reflections of the wave pattern from the side walls of the tank.

Details of the force balance used to measure X and Y, the wave gauge used to measure Z, and the calibration procedure are given in References (3), (4) and (5). The signals are recorded visually on a Visicorder tape and are

then sent from the Minneapolis Honeywell amplifiers directly to the PDP 11 digitizing channels for retention on magnetic disc storage for later retrieval and analysis. Calibrations are taken before and after a test series and/or at the beginning or end of a test day. Zeros are taken on all three data channels before each run.

Zeroed and calibrated data are taken for several different model configurations, each run at the same speed. Usually three or four runs are made to obtain two sets of pairs at the same speed. The model variation could be a bow bulb of a specified shape, some other non-bow located protuberance fitted port and starboard as compared with the bare hull, or a combination of these. A simple computer calculation is used to produce the corresponding wave resistance coefficient C_w.

The question now is raised, how best to use these results? One could make a very simple "better or worse" comparison, i.e. is C_{w1} or C_{w2} for the hull with a certain size bulb or protuberance fitted, greater or smaller than the bare hull result C_{w0}? A more quantitative measure would be the percentage savings, m_1 or m_2, of the base hull wave resistance as a result of fitting the bulb or protuberance tested:

$$m_1 = (C_{w0} - C_{w1})/C_{w0}, \quad m_2 = (C_{w0} - C_{w2})/C_{w0}$$

Or, a more analytical optimization approach, as described in the following, can be used.

As discussed in more detail in References (3) and (4), a single change optimization theory based on assumed linearity of the additional bulb wave effect to some bulb size parameter $k^{(n)}$ (i.e. linear dimension (n = 1), area (n = 2) or volume (n = 3)) can be developed to predict the optimum ratio $k_{1\ opt}$ of the best bulb to the bulb tested and the corresponding minimum resistance coefficient $C_{w\ opt}$. The theory shows:

$$k^n_{1\ opt} = A_1/B_1$$

Where: $A_1 = 2C_{w0} - C_{w10}$

$B_1 = 2(C_{1w} + C_{w0} - C_{w10})$

and $C_{w1\ opt} = (1 - k^n_{opt})\ C_{w0} + 1/2\ k^n_{opt}\ C_{w10}$

Where C_{w10} is a hypothetical cross wave resistance term based on mixing the XY signals with and without the bulb. Details of the above theory and assumptions are given in References (3) and (4). Challenging problems are the need to carefully match speeds and stack records for the C_{w10} calculation and the basic "zero divided by zero" nature of the equation for $k^n_{1\ opt}$.

The above single change theory can also be applied to a protuberance and the single change optimum $k_{2\ opt}$ and corresponding optimum wave resistance coefficient $C_{w2\ opt}$ derived from a second set of tests. (The bare hull test does not need to be repeated.)

A "two change" optimization theory can be derived in which two variations (i.e. a bow bulb and a forebody protuberance) are made independently and the same assumption of linearity is made with respect to the magnitudes k_1 and k_2 of either. The derivation of this theory is given in Appendix A. The resulting equations, based on results of the

three sets of tests: 0 = bare hull, 1 = bulb or change-1, and 2 = protuberance or change-2 are:

$$k_{1\,opt} = \frac{\begin{vmatrix} A_1 & C \\ A_2 & B_2 \end{vmatrix}}{\begin{vmatrix} B_1 & C \\ C & B_2 \end{vmatrix}}$$

$$k_{2\,opt} = \frac{\begin{vmatrix} B_1 & A_1 \\ C & A_2 \end{vmatrix}}{\begin{vmatrix} B_1 & C \\ C & B_2 \end{vmatrix}}$$

Where: A_1 and B_1 are as defined previously and A_2 and B_2 are as A_1 and B_1 with 2 replacing 1,

and: $C = 2C_{w0} - C_{w10} - C_{w20} + C_{w12}$

If a test is also run with both changes, i.e. 3 = 1 + 2, then C_{w3} can be calculated and we have:

$$C = C_{w3} + C_{w0} - C_{w1} - C_{w2}$$

It can be seen that the above two change optimization formulas will reduce to the single change formulas by setting $C = 0$.

Reference (3) also describes the use of clay models of the bulbs and protuberances made from plaster molds as a quick and effective means of producing these hull form changes so that runs can be made under essentially identical calibrations. This practice also leads to great advantages where bulb shape changes are also being considered, as these can be easily accomplished using clay.

The bulb-protuberance geometry and locations are defined in Figure 2.

EXPERIMENTS AND RESULTS

General

Experiments were continued in 1982 on a 5.5 foot model of the Mar Ad "Security Class" Mobilization Ship previously tested (7). The model had been adopted from the previous 5.0 foot short hull model of the original Multi-Purpose Mobilization Ship by adding a reduced parallel middle body and changing the scale ratio from 112:1 to 121.8:1. The model particulars and test conditions are given in Table 2. The present tests include three speeds (design speed ± 5 percent) and three different load conditions from full load to light ballast. Bulbs included a Kawasaki (8) type stern bulb of arbitrary shape, and a new bow bulb with a more vertically distributed sectional area equal to the design elliptical bulb B-1. The latter was an attempt to utilize experience from the previous ballast bulb results in Reference (2) to come up with a better compromise over the range of loadings. The former took advantage of the ongoing research program to look at the latest fad, the stern bulb, from a wave reduction point of view.

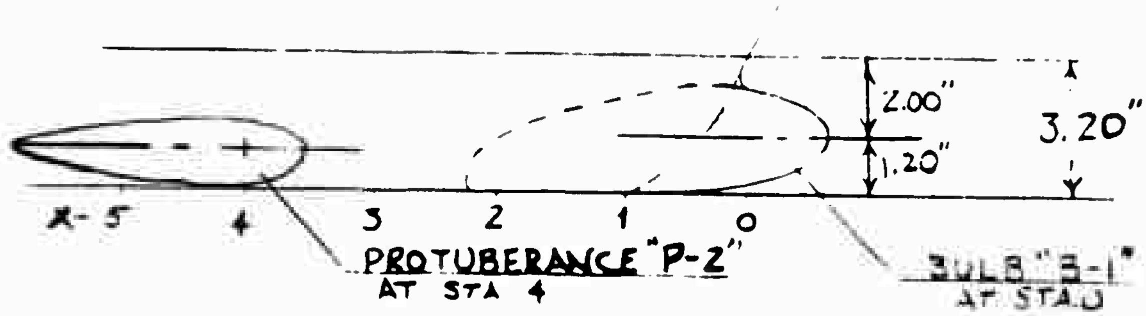


FIGURE 2: BULB AND PROTUBERANCE LOCATIONS

TABLE 2
MODEL PARTICULARS AND TEST CONDITIONS

Maritime Administration "Security" Class Mobilization Ship

		Item	Full Scale	Model*
L	=	LBP, Ft.	670.0	5.501
B	=	Beam, Ft.	105.5	.866
S	=	Wetted Surface, Ft^2	79,681	5.371
V	=	Speed, Knots	21.2	3.244 ft/sec
F_r	=	Froude Number	.245	.245
Δ	-	Full Load Displacement	40,050 LTSW	48.38 lb. FW**
	-	Med. Ballast Displacement	33,260 LTSW	40.20 lb. FW**
	-	Light Ballast Displacement	25,390 LTSW	30.69 lb. FW**

Draft H (Ft.)	Fwd	⊗	Aft	Fwd	⊗	Aft
			(Inches)			
Full Load	30.0	30.0	30.0	2.96	2.96	2.96
Medium Ballast	22.5	25.0	27.5	2.22	2.46	2.71
Light Ballast	15.5	20.0	25.0	1.48	1.97	2.46

* Scale ratio λ = 121.8

** With full size elliptical bulb B-1 or equivalent. For no bulb deduct 0.48 lb. For stern bulb add .12 lb.

In addition to the above, bulb protuberance combinations as shown in Figure 2 were run at full load to explore the effect of such combinations and to check out the validity of the proposed two-change theory as well as the effectiveness and practicability of running tests and reducing the data for this more complicated type of optimization.

It was planned to carry out all the foregoing tests in the winter of 1982, however, malfunction of the model tank drive system resulted in curtailing the winter series and running the remaining tests, including the ballast bulb variations and a check test on the winter two-change tests, during the summer.

Stern Bulb Tests

Tests were run in the winter of 1982 on a typical Kawasaki type stern end bulb (8) using the one change analysis scheme. While no published drawings of such a bulb were available, Reference (8) indicated that the optimum stern bulb width for a container ship Model SR 138 should be 1 1/2 percent of the waterline length, which would correspond to a 1.0 inch width for the 5.50 foot model. Actually, a 1.25 inch bulb width was adopted. It will be seen that the optimum k value deduced from the experiments was 0.9 thus confirming the advice.

The stern bulb shape and dimensions adopted are shown in Figures 3 and 4 (photos). The profile was based on a sketch in Reference (8) but the other shape characteristics were arbitrary. The bulb itself was made of clay and held on by aid of a thin aluminum fin which was left on for the bare hull tests. Tests were run at the design Froude number $F_r = .245$ at full load.

Results of the stern bulb tests are shown in Table 3. These tests stretched the accuracy of the one change optimization method way beyond any previous tests due to the very small change in wave pattern involved. As previously, four run combinations were produced by two sets of run pairs and the integrals calculated and corrected to resistance coefficients C_w. These were then averaged and the optimization formulas were applied to the averaged values to produce the results k_{opt} and m_1. The latter indicates that the

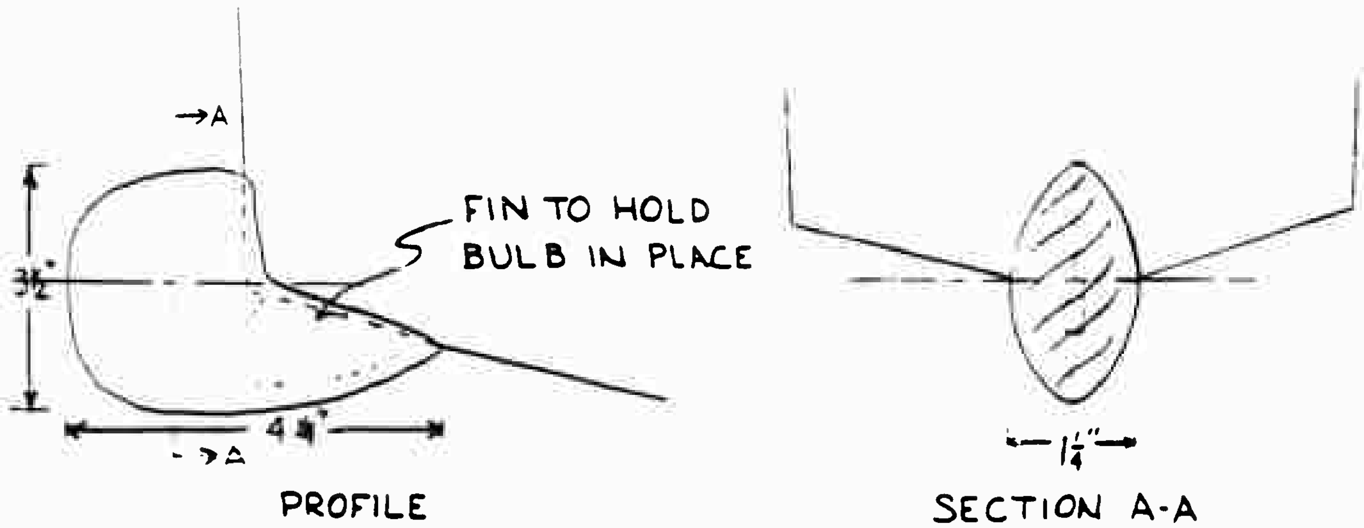


FIGURE 3A: KAWASAKI TYPE STERNBULB
FOR MARAD HULL
(NOT TO SCALE)

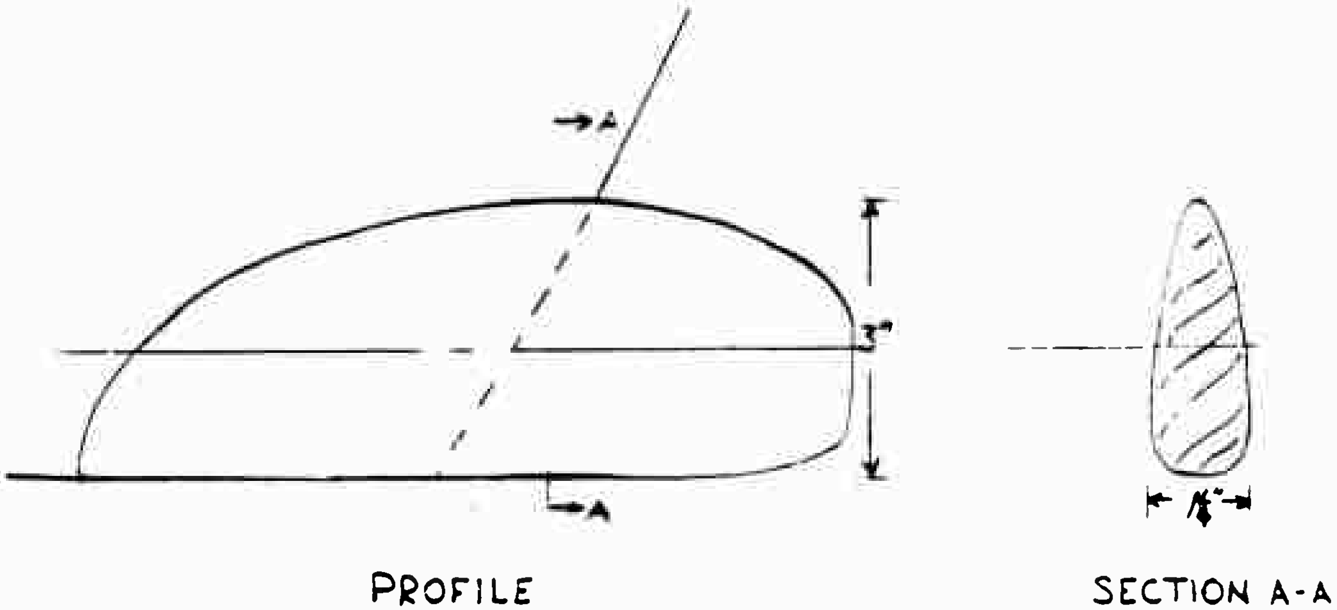


FIGURE 3B: VERTICAL BULB, "VB", FOR
MARAD HULL

(NOT TO SCALE)

saving in wave resistance due to the fitting of the stern bulb was about 6.7 percent of the total bare hull and the former that the optimum stern bulb size should be 91 percent of that fitted. As mentioned before, 91 percent of the 1.25 inch bulb width gives an optimum stern bulb width of 1.13 inches. Thus, the optimum stern bulb width predicted is very close to that recommended in (8), however, the percent saving in resistance for a similar hull is considerably less than that claimed. It should be kept in mind that the present technique deals with the linear wave production only and does not include any other potential savings in non-linear wave or separation phenomena.

TABLE 3

Evaluation of Stern Bulb for Security Class MMS

(No Truncation)

$\times 10^3$

{Run Pair}	C_{w0}	C_{w1}	C_{w10}	k_{opt}	m_1%
{29, 25}	.197	.173	.356	1.33	12
{29, 28}	.196	.187	.367	.76	5
{31, 25}	.189	.173	.348	1.05	8
{31, 28}	.188	.187	.357	.52	1
{29, 25} {31, 28}	.193	.180	.357	.91*	6.7

* Calculated from averaged C_w's

FIGURE 4: PHOTOS OF STERN BULB
FITTED ON SECURITY MMS

The foregoing results do not include truncation effects but it is not expected that inclusion of these effects will change the results in any important way for such small changes. The winter 1982 test series was subjected to a partial malfunction of the Minneapolis Honeywell Power Supply during the test period resulting in problems in the calibrations of wave height and of the force components X and Y before and after the test runs. The non-truncated predictions of k_{opt} and m_1 do not depend on calibration, thus affording another reason for their use.

Further Ballast Bulb Tests

The search for a better bulb shape (area distribution) at medium and light ballast, begun in the previous Mar Ad research program (2), was continued. Table 4(c) of Reference (2) seemed to indicate that about half the full elliptical bulb would be optimum at the latter condition. Using clay as before, a vertically

TABLE 4: 1982 TEST RESULTS

FOOTNOTES:	(1)				(2)	(2)	(3)	(5)	(6)	(4)	(5)	(2)	(2)	(3)	(5)	(6)	(4)	(5)
DATE	CONFIG.	F_r	LOAD	RUNS: N_0, N_1 N_0, N_1	$10^3 C_{w_0}$ T	$10^3 C_{w_1}$ T	$10^3 C_{w_{10}}$ T	m_1 % T	(k^n_{opt}) T	$C_{w_{opt}}$ T	m_{opt} % T	$10^3 C_{w_0}$	$10^3 C_{w_1}$	$10^3 C_{w_{10}}$	m_1 %	(k^n_{opt})	$10^3 C_{w_{opt}}$	m_{opt} %
3/02/82	B-2	.245	Full	17, 19 18, 20	-------	-------	-------	NOT EVALUATED	-------	-------	-------	.1659 (7)	.0716 (7)	.1854 (7)	56.8	1.41	.0627 (7)	62.7
"	P-4	"	"	17, 15 18, 16	-------	-------	-------	NOT EVALUATED	-------	-------	-------	.1659 (7)	.1687 (7)	.2992 (7)	-1.7	.46	.1584 (7)	4.5
3/03/82	SB	"	"	29, 25 31, 28	-------	-------	-------	NOT EVALUATED	-------	-------	-------	.193 (7)	.180 (7)	.357 (7)	0.7	.91	.1798 (7)	6.8
7/06/82	.7 B-1 + .3 P-4	"	"	15, 5 16, 6	.2158	.0746	.1741	65.4	1.10	.0742	65.6	.2058	.0592	.1495	71.2	1.13	.0577	72.0
"	.3 P-4	"	"	15, 8 16, 10	.2158	.1912	.3935	11.4	1.41	.1889	12.5	.2058	.1803	.3727	12.4	1.46	.1774	13.8
7/07/82	VB-1	"	"	34, 23 35, 25	.2177	.0703	.1237	67.7	.948	.0700	67.8	.2106	.0511	.1004	75.7	.994	.0512	75.7
"	"	"	Medium Ballast	39, 21 40, 22	.2057	.1038	.0206	49.6	.676	.0736	64.2	.1925	.0813	-.0140	57.8	.769	.0391	79.7
"	"	"	Light Ballast	42, 19 43, 20	.1592	.1144	.0954	28.1	.627	.0893	43.9	.1347	.0904	.0473	32.9	.625	.0653	51.5
"	"	.233	Full	37, 27 38, 28	.1749	.0356	.0729	79.6	1.066	.0356	79.6	.1634	.0304	.0575	81.4	.988	.0304	81.4
"	"	.257	"	34, 23 35, 25	.2874	.1376	.2895	52.1	1.053	.1372	52.3	.2478	.0929	.2057	62.5	1.073	.0323	62.8

(1) VB = Vertical Bulb; SB = Stern Bulb, 1 or 2 = Full or Half Size.

(2) $10^3 C_{w_k} = \frac{2000}{F_r^2 SL} (I_k + \frac{1}{2} \overline{AB} A_k^2)$

(3) $10^3 C_{w_{10}} = \frac{2000}{F_r^2 SL} (I_{10} + \overline{AB} A_0 A_1)$

(4) $C_{w_{opt}} = C_{w_0} (1 - k^n_{opt}) + \frac{1}{2} k^n_{opt} \; C_{w_{10}}$

(5) $m_k = 100 \left(\frac{C_{w_0} - C_{w_k}}{C_{w_0}} \right)$ = % Saving by Type of Bulb Fitted

m_{opt} from $C_{w_k} = C_{w_{opt}}$ = Greatest Possible Savings

(6) Ratio of Best Bulb to Bulb Tested, i.e. 2.0 for B 2 would agree with 1.0 for B-1, assuming n = 2.

(7) To be used relatively only due to calibration problems.

distributed elliptical bulb, "VB", was formed and tested. Figure 5 illustrates this idea as compared with the other variation considered. Table 4 gives these test results in a format similar to those previously run on other bulb variations and reported in Reference (2).

FIGURE 5

BULB AREA VARIATIONS

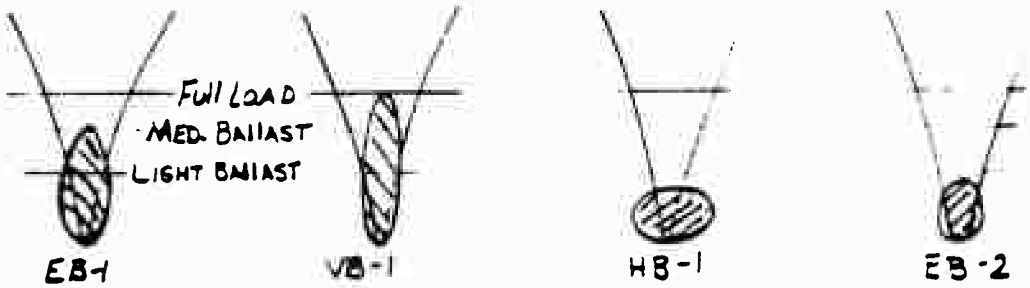


Table 5 also illustrates some other "scenarios" of combined operation as discussed in Reference (2) Predictions are included both with and without truncation. It appears that, depending on the scenario selected, the designed EB is still the best in most cases. The VB idea is competitive with the HB one and the better of the two for some scenarios. It has the additional advantage of not slamming as much should that be a factor.

Sufficient test time was available to investigate the effect of speed variation from the design speed and this was done for the VB at full load. Table 6 summarizes the results and shows that the optimum bulb ratio k is pretty insensitive to speed variation whereas the percentage saving, m, increases at a fairly rapid rate with decreasing speed. This is in agreement with such trends noted in previous Mar Ad research as shown in Figure 7 of Reference (4).

The calibrations taken from the summer 1982 test series were actually quite stable over the two-day test period and give results very compatible with those from the winter 1982 series. This can be seen in Table 4 by comparing C_{w0}'s.

TABLE 5

BALLAST BULB INVESTIGATION SUMMARY INCLUDING NEW SUMMER 1982 VERTICAL BULB

C_w's x 10^{-3}

CODE: WITH/WITHOUT TRUNCATION CORRECTION

"Scenarios" Bulb Description	A: Full Load	B: Med. Ballast	C: Lt. Ballast	D: $\frac{2A + B + C}{4}$	E: $\frac{A + B}{2}$	F: $\frac{A + \ldots}{2}$
0 = Bare Hull	.200 / .190	.175 / .153	.120 / .094	.174 / .157	.188 / .172	.160 / .1[illegible]
VB = Vertical Bulb	.065 / .046	.095 / .073	.105 / .082	.083 / .062	.080 / .060	.085 / .0[illegible]
EB = Elliptical Bulb	.060 / .046	.060 / .046	.096 / .075	.069 / .053	.060 / .046	.078 / .0[illegible]
HB = Horizontal Bulb	.065 / .057	.066 / .050	.107 / .089	.076 / .063	.066 / .053	.086 / .0[illegible]

NOTES: (a) Best Bulb Circled Thus

(b) 1981 and 1982 Series Normalized By Making Bare Hull Full Load The Same In Each Case And Equal To That In The 1981 Tests

TABLE 6

EFFECT OF SPEED CHANGES ON VB-1 AT FULL LOAD

(Truncation Included)

Speed Condition	-5%	Design	+5%
F_r	.233	.245	.257
$10^3\ C_{w0}$	.175	.218	.287
$10^3\ C_{w0} \times (.245/F_r)^2$	.194	.218	.260
k_1	1.01	.95	1.05
m_1	79.6	67.7	52.1

In summary, from a strict wave energy point of view, the original elliptical bulb area distribution seems to be the best overall compromise of those investigated, saving 70 percent of the wave energy at full load.

Two-Change Tests

As mentioned previously, it is possible to construct an optimization approach based on the same assumption of linear wave superposition considering two hull form changes simultaneously. Three sets of experimental wave data are needed corresponding to: the bare hull (0), the first change (1) (say a bow bulb) and the second change (2) (say a Station 4 protuberance), and same signal and mixed-signal XY products integrated to predict the optimum values of each change. The method is outlined in the previous section, and the theories given in Appendix A. Great care must be taken to match test speeds. The theory indicates that the two-change values may differ from those predicted by the one-change method applied to each change separately.

Experiments were run on the Mar Ad Model with a bow bulb B-2 (half-size elliptical) and an equal (total) displacement set of Station 4 protuberances P-4. Previous single change tests had

indicated single change optimum values $k_{1\ opt} = 1.40$ and $k_{2\ opt} = .46$, i.e. a combination of a 70 percent full size elliptical bulb and a 23 percent Station 4 protuberance. The two change C_w's without truncation were found to be:

$$
\begin{aligned}
C_{w1} &= .0716 \\
C_{w2} &= .1687 \\
C_{w0} &= .1659 \qquad (\text{all} \times 10^{-3}) \\
C_{w10} &= .1854 \\
C_{w20} &= .2992 \\
C_{w12} &= .1607 \\
C_{w}{'}_{12} &= .1677
\end{aligned}
$$

The latter check i.e. $C_{w12} \cong C_{w'12}$ gives a good confirmation of the theory. The A's and B's are:

$$
\begin{aligned}
A_1 &= .1469 \\
A_2 &= .0325 \\
B_1 &= .1042 \\
B_2 &= .0707 \\
C &= .0078 \text{ (or .0149 using } I'_{12})
\end{aligned}
$$

These give combined change k_{opts}:

$$
\begin{aligned}
k_{1\ opt} &= 1.38 \text{ (or 1.38)} \\
k_{2\ opt} &= \ .31 \text{ (or .12)}
\end{aligned}
$$

And single change k_{opts}:

$$
\begin{aligned}
k'_{1\ opt} &= 1.41 \\
k'_{2\ opt} &= \ .46
\end{aligned}
$$

as given in Table 4.

Incorporating the above two-change optimums, the opt $C_{w\ opt}$ becomes:

$$C_{w3\ opt} = .0597$$

thus, predicting a saving of 64 percent of the bare hull wave resistance $C_{w0} = .1659$. As mentioned previously, because of calibration difficulties, the above C_w's should not be compared quantitatively with those from the previous year's (1981) results or with those from the summer of 1982.

The above predicted optimum combination was actually run in the summer of 1982, reducing the size of the designed bulb and protuberance forms (made of clay) by hand. The resulting net combined wave resistance C_{w3} was found to be:

$$C_{w3} = .0746$$

with $$C_{w0} = .2158$$

thus showing a saving of 65.4 percent of the bare hull wave resistance, very close to that predicted. Moreover, the single change "k_{opt}" value for this combination was found to be 1.10 further confirming the optimum selection.

The above results were also analyzed including truncation corrections. These results and the results without truncation are given in Table 4. The percentage savings predicted without truncation seem always to be higher than those with truncation. The significance of this result, assuming it to be a general one, is not understood at the present time.

It should be noted that most (88 percent) of the bare hull wave resistance saving is due to the bow bulb and only a small amount (12 percent) due to the Station 4 protuberances; however, the latter do seem to have a beneficial effect that could be more important at a different (smaller) Froude number.

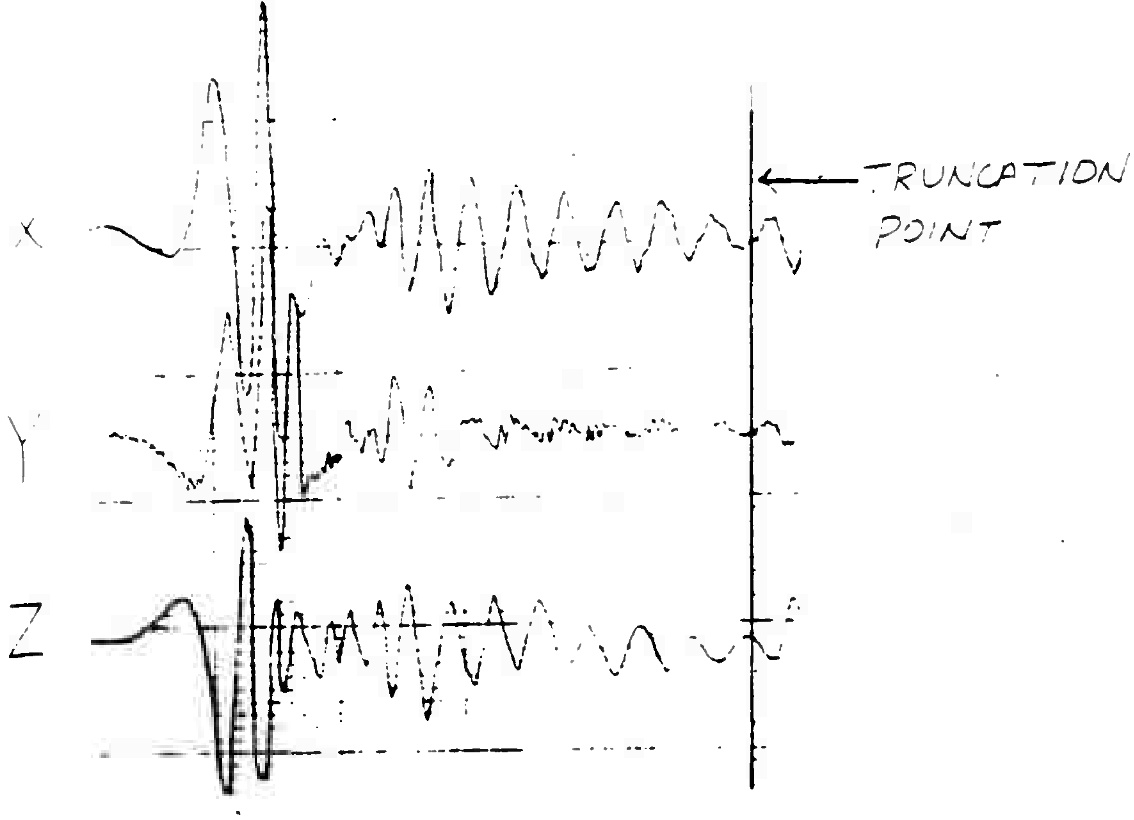
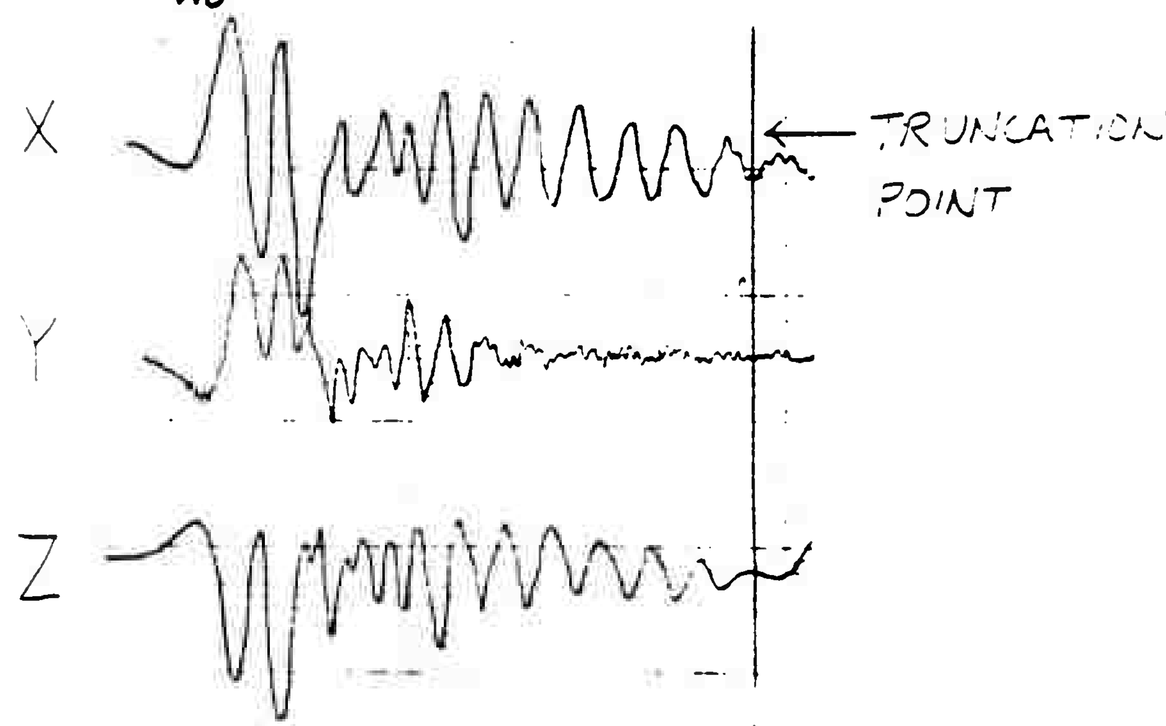


FIGURE 6: COMPARISON OF SIGNALS

A: BARE HULL (RUN EPL014) WAVE RECORDS CORRESPONDING TO $C_{W_0} = 0.2158$



B: OPTIMUM BULB-PROTUBERANCE COMBINATION (RUN EPL005) WAVE RECORDS CORRESPONDING TO $C_{W_0} = 0.0746$

General (Again)

In all of the comparisons involving the above results, including the stern bulb, ballast bulbs and two-change combinations, some from the same week of testing and others as much as a year apart, it should be emphasized that the very nature of the process of deriving optimums, etc., and the repeatability of the data and speed matching needed to assess small changes in wave profiles, will produce differences that might not be the result of real physical cause-effect relationships but could be merely "scatter". At this stage, it is proposed that a difference of 7 percent in any criterion (i.e. a m_1 or percent saving of 66 percent as opposed to 70 percent) not be assumed to prove a trend but one of 10 or 15 percent (60 percent versus 70 percent) be definitely so considered.

The question of the effect, if any, of model size on the foregoing results should be addressed. Wave production is of course a predominantly ideal flow phenomenon. However, the boundary layer thickness is relatively larger for the model than for the ship. This is also true when comparing the smaller model with the larger model. It also grows with distance from bow* to stern for either and has the effect of softening the hull form (i.e. decreasing slopes, etc.) and therefore decreasing its wave producing effectiveness. Thus adopting the foregoing reasoning, it can be argued that the stern bulb tests would be more susceptible to scale effects than those involving the bow bulbs and those involving the Station 4 protuberences somewhere in between. It might be that larger scale wave survey tests on the stern bulb would uncover larger possible savings than the present tests. It would be very surprising, however, if any such important difference due to scale were found in the case of the bow bulb findings.

----

* At the very bow, the boundary layer thickness is zero for all cases.

Finally, having established the value of an analytical experimental method using wave signals to demonstrate a saving of about 2/3 of the bare hull wave resistance, one might wonder if a saving of energy of such a magnitude would be obvious by comparison of the signals themselves. Figure 6 was prepared in an attempt to answer this question. The three signals involved, the XY forces and the Z wave elevation (used for calibration and truncation only) are displayed for: (a) the bare hull and (b) the greatest saving (B-.7 and P-.15) at the same calibration. The signals had to be sketched as the data in the project is available only on a computer disc. We leave it to the reader; if you had seen the wave elevation Z in Figure B in comparison to that in A, would you have concluded that a major saving in wave energy dissipation had occurred? Or if you went further and looked at the X and Y signals and imagined them multiplied (no fair actually doing the multiplication!), would you? An interesting question!

TABLE 7

RESULTS OF EVALUATION OF PREDICTED OPTIMUM BASED ON TWO CHANGES

Froude Number F = .245 Full Load

Change*		1	2	3 = Comb.
Predicted:	k	1.38	0.30	--
2/82	m%	56.8%**	1.7%	64.0%
Tested:	k***	--	1.41**	1.10
7/82 Tests	m%	--	12.5%**	65.9%

* Change 1: Bulb B-2 or EB-1 at Station 0

Change 2: Protuberance B-2 at Station 4 P/S

** Based on changes separately

*** These k-values relate to the changes actually tested i.e. 1.4 B-2 (or 0.7EB-1) and 0.3 B-2 at Station 4.

CONCLUSIONS AND RECOMMENDATIONS

Based on the foregoing results, the following conclusions are drawn and recommendations made:

Application of the now well-established XY wave survey optimization procedure in the Webb Model Tank to the practical problem of searching for an optimum hull form shape can be extended to other cases such as stern bulbs and a bow bulb - forebody protuberance combination in a practical and useful way.

A two-change optimization theory developed to analyze the latter results is shown to be valid.

The Kawasaki stern bulb is shown to have a beneficial effect on reducing wave resistance but smaller (7 percent) than seems to be claimed. This result could be modified by scale effects.

For the Mar Ad "Security Class" Mobilization Ship, the designed elliptical bulb is still the best overall compromise among a series of other shapes tried for combined loadings, now including a vertically distributed area bulb.

The wave energy reductions possible by using hull form changes are quite impressive, about 67 percent. They are not readily identifiable by simple comparison of wave records.

Variations in wave production power as a result of propeller mean wake changes do not seem to be of importance in the present case.

Improvements in stability of test calibration and ease of analysis procedures were also achieved.

It is recommended that the above method be further utilized and applied at Webb and at other model tanks to investigate and assess possible savings in wave power expended by ships under practical operating conditions.

APPENDIX A

TWO-CHANGE THEORY

The XY method is based on a simple integration of the X and Y forces exerted by the waves on a vertically oriented circular cylinder as shown in Figure A-1. We assume that each force component is linearly related to the waves produced by the ship hull with two changes as depicted, and that the waves are a linear superposition of those due to the hull, change-1 (bow bulb illustrated) and change-2 (equal port-starboard protuberances shown). The basic XY integral is:

$$I = \rho g \int_{X_B}^{\infty} X'Y'dx + \text{Trunc.}$$

$$X' = X/C_1 = \text{Wave Height}$$

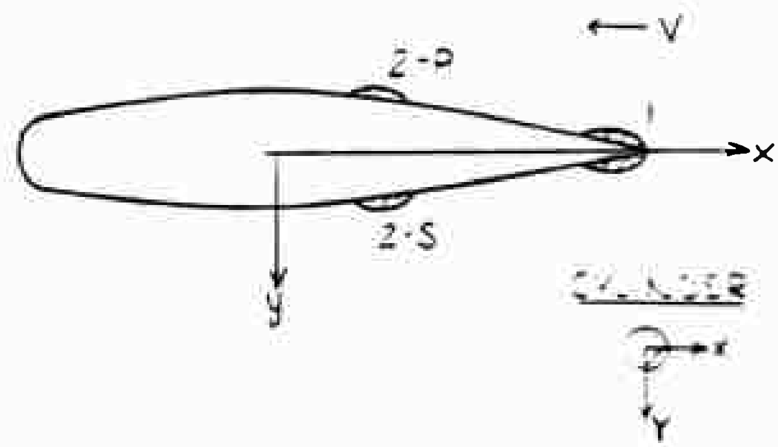


FIGURE A-1: HULL AND TWO CHANGES

The signals are (X only shown):

X_0 Bare Hull Signal

X_1 With Bulb Signal as Tested

X_2 With Protuberance Signal as Tested

X_{1+2} With Bulb and Protuberance

We introduce control parameters:

k_1 Ratio of Bulb Considered to that Tested

k_2 Ratio of Protuberance Considered to that Tested

The assumed XY signals are:

$$X_{1+2} = X_0 + k_1 (X_1 - X_0) + k_2 (X_2 - X_0)$$

$$Y_{1+2} = Y_0 + k_1 (Y_1 - Y_0) + k_2 (Y_2 - Y_0)$$

The XY integral becomes:

$$I_{1+2} = \rho g \int X_{1+2} Y_{1+2}\, dx$$

Combining, we get:

$$I_{1+2} = I_0 + k_1 (I_{10} - 2I_0) + k_2 (I_{20} - 2I_0) +$$

$$k_1 k_2 (2I_0 + I_{10} - I_{20} + I_{12}) + k^2_1 (I_0 + I_1 - I_{10}) +$$

$$k^2_2 (I_0 + I_2 - I_{20})$$

Where:

$$I_r = \rho g \int X_r Y_r\, dx$$

$$I_{rs} = \rho g \int (X_r Y_s + X_s Y_r)\, dx$$

To optimize, we set:

$$\frac{\delta I_{1+2}}{\delta k_1} = 0$$

$$\frac{\delta I_{1+2}}{\delta k_2} = 0$$

And obtain:

$$B_1 k_{1\,opt} + C k_{2\,opt} = A_1$$

$$C k_{1\,opt} + B_2 k_{2\,opt} = A_2$$

Where:

$$A_{1,2} = 2I_0 - I_{1,20}$$

$$B_{1,2} = 2(I_0 + I_{1,2} - I_{1,20})$$

$$C = 2I_0 - I_{10} - I_{20} + I_{12}$$

Thus, the two change optimum values are.

$$k_{1\,opt} = \frac{\begin{vmatrix} A_1 & C \\ A_2 & B_2 \end{vmatrix}}{\begin{vmatrix} B_1 & C \\ C & B_2 \end{vmatrix}}$$

$$k_{2\,opt} = \frac{\begin{vmatrix} B_1 & A_1 \\ C & A_2 \end{vmatrix}}{\begin{vmatrix} B_1 & C \\ C & B_2 \end{vmatrix}}$$

For a single change, we set $k_2 = 0$ and obtain:

$$k_{1\,opt} = A_1/B_1 \text{ as before}$$

For C small ($C^2 \ll B_1B_2$) we have:

$$k_{1\,opt} = k'_{2\,opt} - C/B_1\, k'_{2\,opt}$$
$$k_{2\,opt} = k'_{2\,opt} - C/B_2\, k'_{1\,opt}$$

The evaluation requires three tests to be run:

0 - Bare Hull

1 - Model with Bulb Fitted

2 - Model with Protuberances Fitted

and the corresponding single and mixed integrals: I_0, I_1, I_2, I_{10}, I_{20} and I_{12} to be calculated. If a fourth test: 1 + 2 = 3, i.e. model with both bulb and protuberance fitted, is run and I_3 calculated then I_{12} can be replaced by a predicted I'_{12}:

$$I'_{12} = I_3 - I_0 - I_1 - I_2 + I_{10} + I_{20}$$

$$\text{and then } C' = I_3 + I_0 - I_1 - I_2$$

APPENDIX B:

CALIBRATIONS IN THE SUMMER OF 1982 TESTS

Part of the current research program involves developing good procedures and equipment for obtaining valid calibration factors. During some test periods, in particular that in the winter of 1982 when the Minneapolis Honeywell power supply was subject to intermittent failure as discussed, the calibrations seemed to shift and be subject to interpretation. Accordingly, more care was taken during the summer tests to investigate possible problems and to take data to clarify this question.

The summer 1982 calibration data is summarized in Table B-1. The calibration procedures used are those described in Reference (4). These essentially consist of a static calibration of the wave wire using a known movement, a relative static calibration of the X and Y force balances using a constant weight force in perpendicular directions, and a dynamic calibration of the X signal by analysis of the model runs themselves. The latter has been improved using a new computer analysis of the tail ends of the run signal described in Reference (2). While previously only a few of the latter, usually the bare hull* runs, were analyzed to provide an average Z/X value, in the present case all 27 runs were so analyzed to investigate any time or amplitude based trends and/or daily scatter.

----

*The bare hull runs have larger tail end signal amplitudes since more wave resistance is present.

TABLE 3-1

STATIC AND DYNAMIC CALIBRATIONS FOR SUMMER 1982 TESTS

Note: All at F_r = .245, i.e. Same Speed Unless Noted

DATE	TIME	RUN	10^3 C_Z 1	Y/X 2	Z/X 3	10^3 C_X 4	10^3 C_Y 5	NOTES
August 6		2	.670	1.066	--			"AM" Calibration
"	15:00	5	--	--	.821			
	15:07	6	--	--	.736			
"	15:31	8	--	--	.728			
"	15:40	10	--	--	.625			
"	16:09	14	--	--	.655			
"	16:14	15	--	--	.602			Bare Hull Run
"	16:24	16	--	--	.655			" " "
"		17	.679	1.053	--			"PM" Calibration
August 6	AVERAGE		.675	1.060	.689	.465	.439	
August 7		18	.662	1.026	--			"AM" Calibration
"	13:48	19	--	--	.674			
"	13:52	20	--	--	.638			
"	14:01	21	--	--	.731			
"	14:06	22	--	--	.769			
"	14:16	23	--	--	.786			
"	14:28	25	--	--	.696			
"	14:46	27	--	--	.661			Slower
"	14:50	28	--	--	.612			"
"	14:54	29	--	--	.770			Faster
"	15:00	30	--	--	.807			"
"	15:14	31	--	--	.738			Bare Hull Faster
"	15:19	32	--	--	.713			" " "
"	15:33	34	--	--	1.097			" " "
"	15:38	35	--	--	.723			" " "
"	15:49	37	--	--	.863			Bare Hull Slower
"	15:53	38	--	--	.770			" " "
"	16:06	39	--	--	.806			
"	16:12	40	--	--	.804			
"	16:30	42	--	--	.906			
"	16:34	43	--	--	.964			
"	"	44	.664	1.048	--			"PM" Calibration
August 7	AVERAGE		.663	1.037	.776	.514	.496	
August 6 & 7	AVERAGE		.669	1.049	.754	.504	.481	Used For Analysis
August 6	BARE HULL RUN AVERAGE			--	.629			
August 7	" " " "			--	.817			

1. Ft. Wave Ht. Per Digital Signal Unit. Derived From Static Movement of Wave Wire ±0.50 inches
2. Derived Statically From Placing Equal Weight Force On Each leg
3. Derived Dynamically From Computer Program Comparing Amplitudes of Sinusoidal Tail End Portions of Z and X Signals For Each Run
4. $C_X = C_Z \times Z/X$, Average Values Used
5. $C_Y = C_X \div Y/Z$, Average Values Used

The results are given in Table B-1 with static calibration runs included in chronological order with the test runs which also serve as dynamic calibration runs as discussed. It can be seen that the former, which were taken before and after each day's test series, are quite stable and essentially give the same values on a given day or between days. The latter are subject to a fair amount of scatter, about $\pm$ 20 percent about a mean of .77. There does not seem to be any definite trend during a particular day. One possibility is that the relationship is not linear with wave height; in that case the set of bare hull runs, for which the wave resistance and therefore the wave amplitude should be larger, should differ in a consistent way from the whole set. It can be seen that this is not the case. Those from August 6 give smaller and those from August 7 give a larger answer. Another possibility is a speed variation. Table B-1 identifies those whose speeds which were slower or faster than the design speed. Again, no trend is evident. It was concluded that the process was one of experimental scatter and an overall average of both days was adopted for use in the analysis.

APPENDIX C:

INTEGRATION OF RUN PAIRS [FROM REFERENCE (3)]

The analysis phase of determining κ_{opt}, etc., is challenging. Not only does this require careful matching of pairs of runs with and without the protuberance or bulb in regard to starting points*, run speeds and calibration factors to produce comparable individual XY integrals I_0, I_1 and the mixed integral I_{10}, but the integrals themselves must be calculated accurately using an adequate sampling rate. Figures C-1 and C-2 illustrate the point. In Figure C-1, an actual single run calculation is shown; the XY signals and wave height (Z) signal are given (the latter is needed only for calibration), as are the XY products, which are the integral values, and their running sum which is the integral itself. It is interesting to see what portions of the wave records contribute significantly to the integration. Coincident large XY peaks are very important to this. Furthermore, it is seen that the data sampling rate is just adequate for the calculation in that there are 3-4 data points in the region of the sharpest peaks. Finally, the character of the truncation addition needed at the end of the run can be seen and seems to be in agreement with the assumption of the wave system simplifying to a single plane wave in this region.

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*Use of the automated data acquisition procedure, where the DC signals starts and stops the process, is a great improvement in this regard.

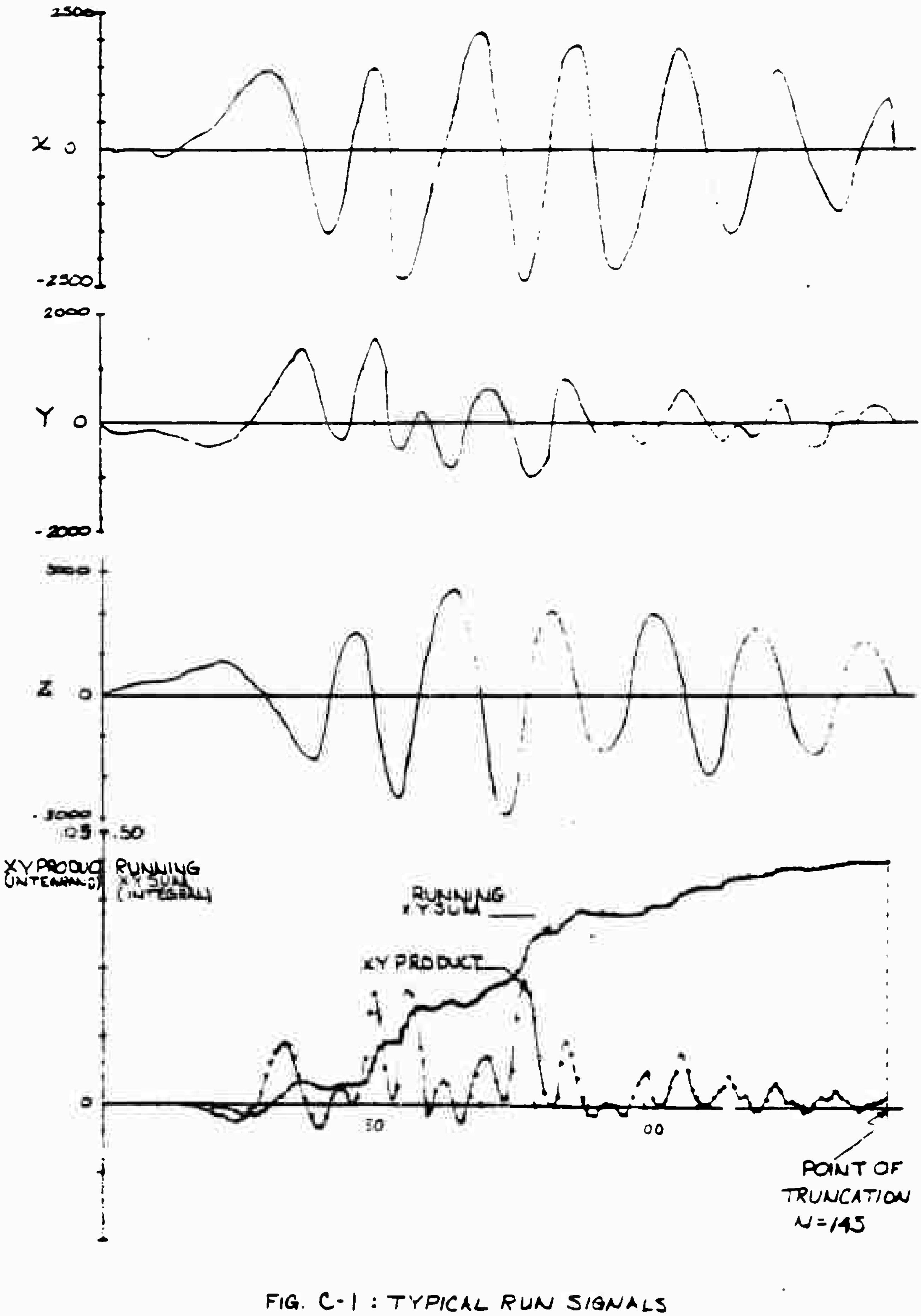

FIG. C-1 : TYPICAL RUN SIGNALS AND INTEGRATION : X, Y, Z, I
RUN # 15

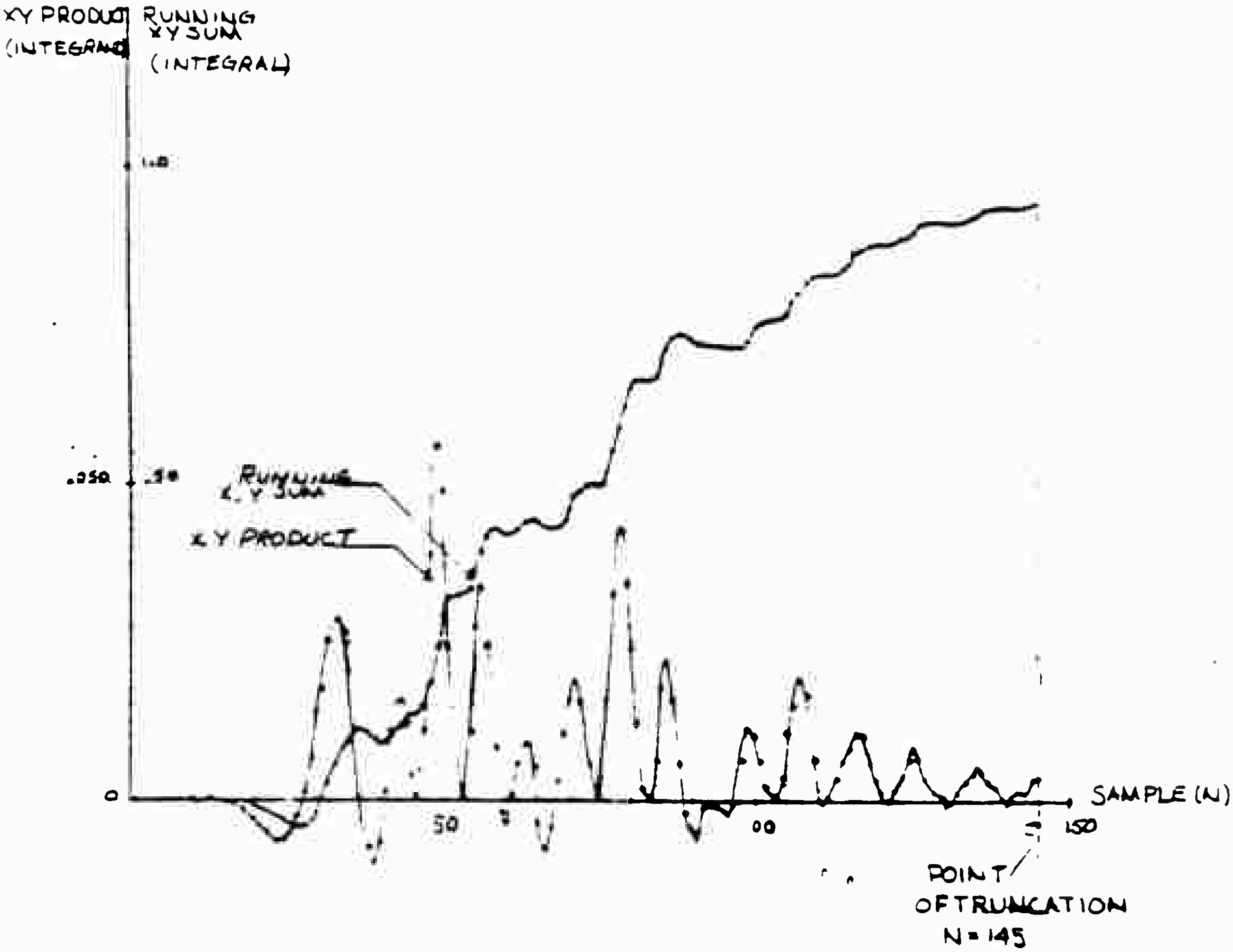

FIG C-2: TYPICAL RUN PAIR INTEGRATION RUNS 4 AND 15

APPENDIX D:

WAKE SURVEY EXPERIMENTS [FROM REFERENCE (2)]

It is possible that savings in wave resistance by addition of bulbs or other hull form changes might be offset (or improved) by changes in the propulsive coefficient due to changes in the nominal wake at the propeller disc, thus, decreasing (or increasing) the net power saving. Such a wake change due to the bulb is expected to be mainly a result of changes in the following wave amplitude at the stern and therefore should be constant over the plane of the propeller disc, except for a minor exponential decay with draft. Thus, in assessing whether any important changes are taking place, it should be sufficient to compare horizontal velocities at propeller hub draft at a sufficient distance either to port or to starboard of the centerline to get away from the boundary layer effects.

Wake assessment experiments as described above were run under the current effort during the summer of 1981 on the Security Class M.M.S. model at the design Froude number at the three different loading conditions used for the wave survey test run the previous winter. Careful attention to the instrumentation, a "CTA" (Constant temperature anemometer hot film probe) and its calibration and cleaning procedure as established for the Webb Model Tank by a previous student thesis gave results that are believed to be consistent and valid for the purpose intended. Also, taking advantage of a calibrated system in place and working another test day was devoted to examining the port-starboard wake profile and time build-up during the run down the tank. Not only are these results interesting in themselves but they show two necessary features of the wake change assessment experiments run during the present investigation:

(a) Port-starboard averaging is necessary to eliminate the effect of any towing eccentricity on the small changes being considered and

(b) Using a lateral distance y to propeller radius R ratio, y/R value of 1.4 to stay outside of the thick boundary layer characteristic of the small 5.5 foot model with a vertical skeg ahead of the propeller. This is clearly shown in Figure D-3.

Figure D-1 shows the calibration curves for the C.T.A. as taken on the morning and afternoon of each test day. The numbers shown are run numbers; they are not related to those for the previous wave survey run numbers but they are consecutive allowing any time dependent or run-length dependent effects, such as the important contamination-cleaning procedure referred to in Reference (7) to be noticed and evaluated.

The wake fractions results obtained by the above procedure are summarized in Table D-1. These are defined as:

$$w = V_m - V_{CTA}/V_m$$

where V_m is the ahead speed of the model and V_{CTA} is the local x-directed velocity measured. Both port and starboard and port-starboard average values are shown for the model with the elliptical bulb EB-1, with the half-size elliptical bulb EB-2 and without any bulb.

It can be seen that there is a small effect of increasing wake with lighter loading but virtually no change due to the bulbs fitted. Other bulb shapes can be assumed to act in the same way. Thus, it is concluded that resistance percentage savings are in effect power percentage savings as well.

During the last test day of the summer 1981 series, the hot film probe constant temperature anemometer (CTA) was used to measure wakes on the 5.501' Mar Ad model (without protuberances). The signals from the CTA were recorded on a brush recorder. The probe was located at the stern of the ship and its horizontal position was varied along a constant depth (probe track) of the axis of the propeller shaft in increments of fractions of propeller radius (y/R). From the brush recorder records, the following was obtained:

1. The average CTA signal, which is proportional to the measured fluid velocity.

2. The "envelope" of the CTA signal, which is a measure of the turbulence. (This is an average of peak to trough values around point C.)

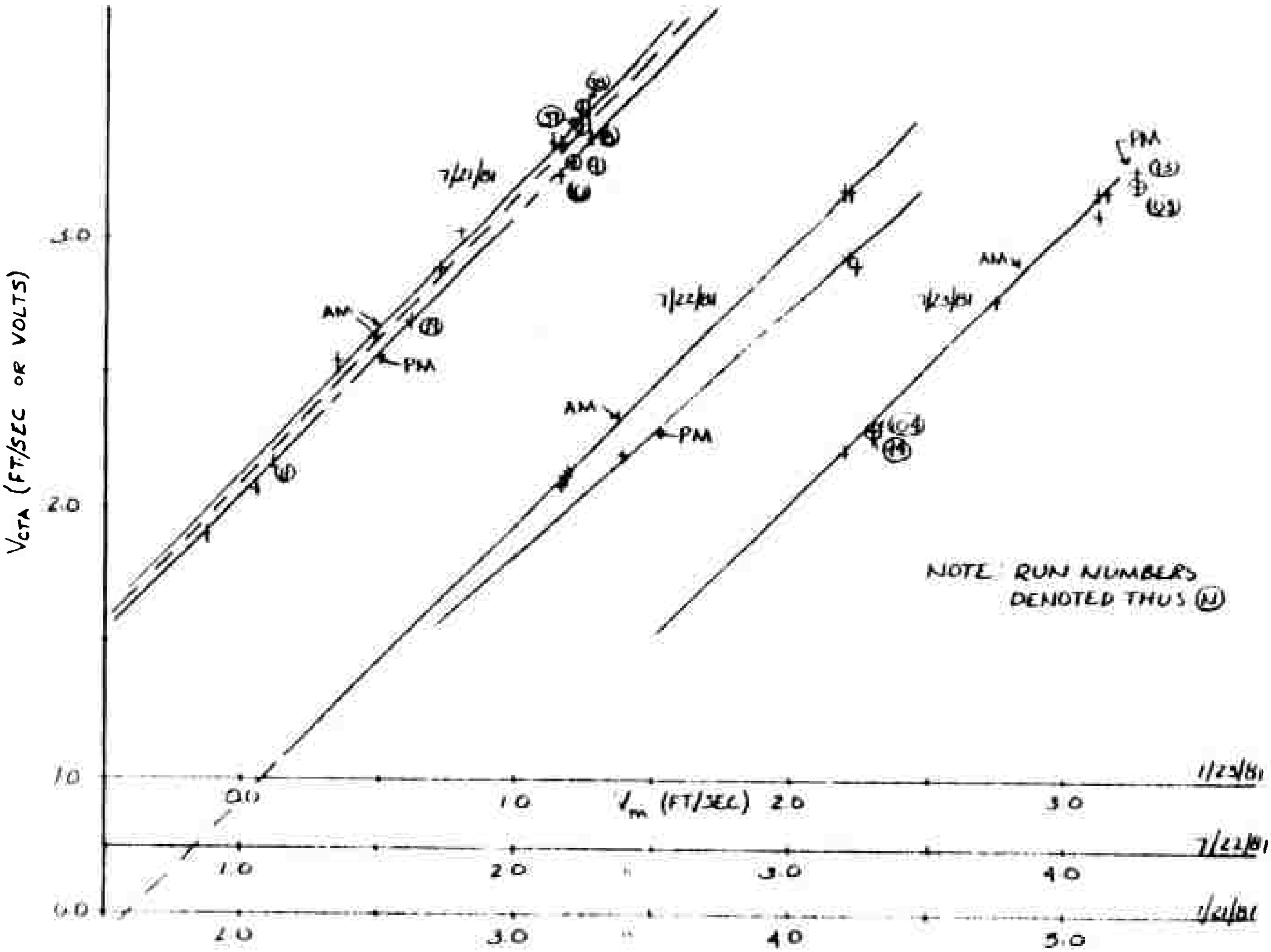

FIGURE D-1: CALIBRATION CURVES FOR L.T.A. WAKE TESTS, PROBE 611

TABLE D-1

VALUES OF WAKE

@ 1.4 y/R FOR "SECURITY CLASS" MMS

	BARE HULL		EB-2		EB-1	
Full Load	P: .10 S: .10	P S Runs: 47, 48-45, 46 Avg: .10	.09 .125	73, 74-75, 76 .11	.10 .10	47, 48-45,46 .10
Med. Ballast	P: .10 S: .13	Runs: 62, 63-60, 61 Avg: .12	.10 .14	71, 72-69, 70 .12	.13 .12	49, 50-51 .125
Light Ballast	P: .12 S: .14	Runs: 56, 57-58, 59 Avg: .13	.11 .13	64, 65-66, 67 .12	.13 .11	54, 55-52, 53 .12

3. The estimated "settling time" (Ts). That is, the estimated time required for the turbulence to reach some state of consistency (no low frequency oscillation).

4. The wake percentage. (Using the measured speed as reference.)

5. The ratio of the CTA envelope to its average = $\frac{\text{No. 2}}{\text{No. 1}}$.

These are tabulated in Table D-2. Table D-3 describes the points on the records marked A-E. The markers on the wall of the tank were used as a distance reference.

The tabulated results in Table D-2 are plotted in Figure D-2. The range for measurements was from 0 to 1.4 y/R fractions of propeller radius on the port side and are reflected on the starboard side. The CTA probe was calibrated so that one of CTA signal closely approximated one foot per second of flow rate. The average speed of the runs tabulated was 3.23 ft./sec. Notice that wake percentage approaches zero on an asymptote as y/R increases and goes to 84.52 percent at y/R = 0. The CTA envelope, which is a measure of the turbulence, reaches a maximum near the point of maximum slope of the percent wake curve.

Figure D-3 shows the foregoing results on the bare hull model as compared with the same model with an elliptical bulb and a longer (24.0 ft.) HSMB model (7) with an elliptical bulb. The results on the same scale model with and without a bulb are practically identical except that the latter shows a port/starboard assymmetry. The differences between the WINA and HSMB results show the effect of model scaling, the longer model having a much thinner wake.

The foregoing results establish (a) that the run time is more than sufficient for the boundary layer to reach steady state and (b) that the small model has a very noticeably thicker boundary layer, thus, requiring measurement of the wave effect on wake at a y/R of at least 1.25 to be outside the region affected by viscosity.

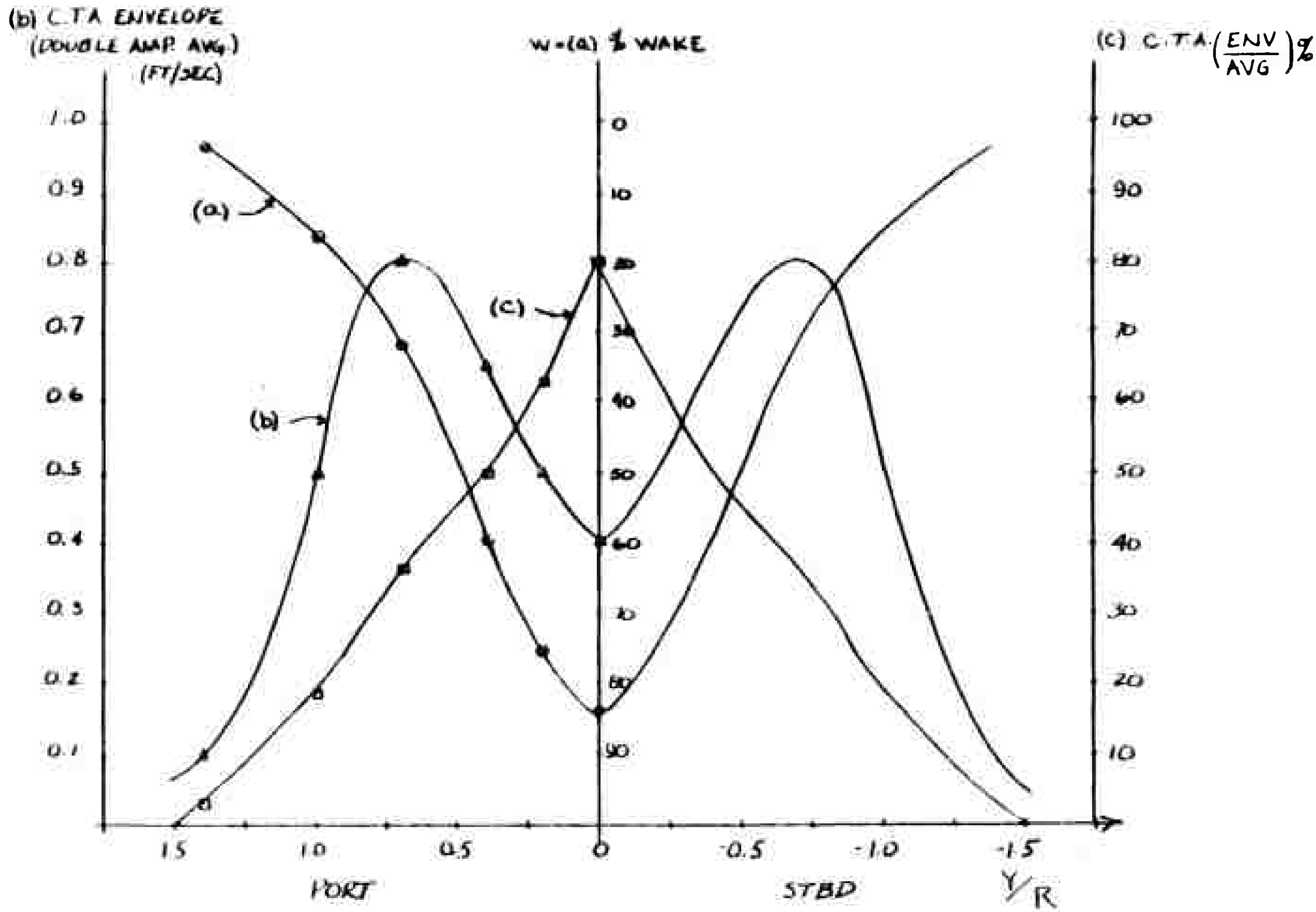

FIGURE D-2: VARIATION OF AVG WAKE AND WAKE FLUCTUATION WITH LATERAL DISTANCE Y/R

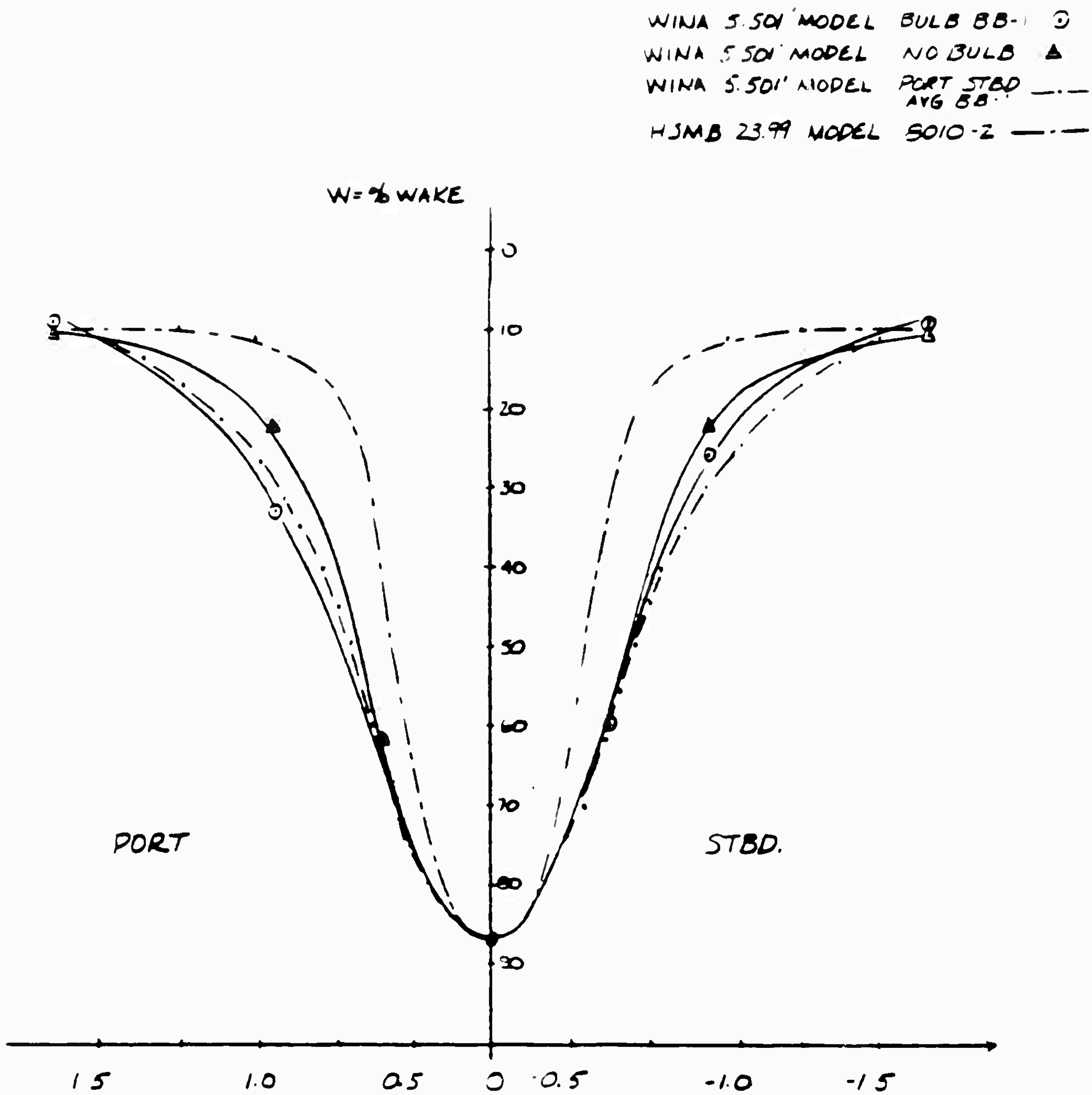

FIGURE D-3: COMPARISON OF WAKE MEASUREMENTS

TABLE D-2

DATA FROM BRUSH RECORDER CHARTS

1 volt = 1 ft/sec

RUN #	y/R	SPEED (ft/sec)	CTA (AVG) (volts)	CTA (ENV) (volts)	T_s (sec)	w - % WAKE	$\frac{CTA(ENV)}{CTA(AVG)}$
2	1.4	3.22	3.10	.1	.64	3.73	.0323
3	1.0	3.24	2.7	.5	.88	16.67	.1852
4	0.7	3.23	2.2	.8	.72	31.89	.3636
5	0.4	3.23	1.3	.65	.72	57.75	.5000
6	0.2	3.23	0.8	.50	1.24	75.23	.6250
7	0.0	3.23	0.5	.4	.70	84.52	.8000
8	no model	3.24	3.25	-	-	-	

TABLE D-3

TEST GEOMETRY

POINT	MARK ON TANK WALL	COMMENTS
A	0	Carriage started
B	3.4	Half way to test region start
C	6.8	Start test region
D	13.5	
E		End of Test Region End of Run

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DISCUSSIONS

Grant R. Hagen
Designers and Planners, Inc.

Are wave cut tests applicable to ship hulls in general? Specifically, in instances where a substantial part of the residuary resistance is associated with wave breaking, as for very full form hulls, is it applicable?

C.C. Hsiung
Memorial University of Newfoundland

I would like to comment on the position of proturberances or side-bulbs for the optimal hull forms. In my earlier theoretical study on optimal hull forms (Journal of Ship Research, Vol. 25, No. 2, June 1981), it was found that the side-bulbs usually appeared to be close to the free-surface or at the mid-draft rather than near to the keel as shown in your testing model. May I suggest that in your later experiments, you may adjust the vertical positions of the side-bulbs to check their effectiveness in wave resistance reduction.